CATAMARAN-TYPE VEHICLES: A LITERATURE SURVEY

by

T. Y. Wu
California Institute of Technology
Pasadena, California

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1. Introduction

A renewed interest in catamaran-type vehicles has emerged in the past decade in connection with the development of unconventional water crafts. This interest has been stimulated by the main advantages that this type of unconventional vehicles may be able to offer, namely,

1. a large, useful deck area (compared with that of conventional ships),
2. a favorable roll stability for various ocean tasks,
3. good seaworthiness characteristics in rough seas, especially when the waterplane area can be made small.

While these major factors and some other related advantages may put the catamaran ship in direct competition with the conventional ship, the development of catamarans has nevertheless encountered several intrinsic difficulties. The principal problems that keep the catamaran from being decisively superior include

1. the poor hydrodynamic feature of large total resistance due to the increased wetted hull surface,
2. the added structural problems resulting from the cross-deck structure between the demihulls, making the payload-to-structural weight ratio less competitive,
3. the potentially severe hydrodynamic force due to wave impact on the bottom of the cross-deck structure when operating in a seaway.

A well-balanced design of a catamaran-type craft will therefore be concerned with an optimal compromise between the motion, power supply, and structural weight considerations. These considerations would primarily depend on the principal design criterion such as the cruise and top speeds, utility functions, required maneuverability constraints, propulsive efficiency, and so forth.

Various attempts have been made, under different design objectives, to overcome and alleviate some of the outstanding disadvantages. In order to improve the hydrodynamic and structural performance, several alternative hull forms have been proposed, thus bringing forth the Modified Catamaran, the Trisec, the Low-Waterplane-Catamaran, and the S^3 (Semi-submerged Ship). With still different mission objectives, further variations have been developed, including the SWATH (small-water plane-area twin hull), CVA (attack aircraft carrier), and the ASR (submarine rescue ship) catamarans. These variations are mostly based on the concept of replacing the classical demihull configuration by three distinct parts, two enlarged underwater displacement hulls, an above-water platform, and vertical connecting struts.

This brief literature survey will cover primarily the hydrodynamic aspects of the new designs that deal with the resistance and ship motion, although some related structural problems will also be included for completeness. A general discussion of the feasibility and main features of sea-going catamarans has been given by Michel (1961), and a comparative evaluation of catamarans relative to conventional ships can be found in the survey article of Mandel (1962).

2. Viscous and Wave-making Resistance

The viscous frictional resistance of a catamaran is generally about twice as high as an "equivalent" monohull ship (defined as one of equal length, total beam and total displacement, while cruising at the same Reynolds number), since the wetted hull surface of the catamaran would be about double that of the latter. The problem of the wave resistance of a catamaran, however, is usually associated with a smaller beam/length ratio for each demihull than that of an equivalent monohull, and may further involve the wave interference effect depending on the hull spacing, the Froude number, and, possibly, an interaction with the viscous effect to cause the flow separation near the ship sterns altered. In still another aspect of motion stability and seaworthiness, the catamaran appears to lie in a quite different realm of performance characteristics from conventional ships.

Barillon (1926) was probably one of the first to have investigated experimentally the resistance of a system of model ships (towed in various relative positions). This work and some analogous wall-effect problems led to a series of theoretical studies by Havelock (1936, 1937, 1940). His first attempt was to represent two equal small spheres in arbitrary relative position at the same depth of submergence by two equal horizontal doublets as the first approximation. With the two spheres abreast, the result shows that each sphere experiences at all stream velocities a higher wave resistance than in solitude, and this added resistance increases with decreasing spacing, reaching at fixed spacing a maximum when the depth Froude number is about unity. With the spheres in other relative positions, the effects of wave interference occur when the following sphere lies within the wave pattern of the leading one, and can be attributed to both the transverse waves and the diverging waves. This fundamental analysis was later extended by Havelock (1937, 1940) to consider the wave resistance and drift force of a ship among free waves, showing that the additional forces may be of the same order as the wave resistance in still water even for waves of small to moderate magnitudes. These problems have also been discussed by Stretensky (1936) based on the Michell type theory.

The wave resistance of a catamaran in a shallow water of uniform depth can be described by the steady motion of a monohull ship parallel to a vertical wall. This problem has been treated, together with other varieties of wall effects, by Lunde (1951) in his expository survey paper (along the line of Havelock's theory), and independently by Eggers (1955), with the Michell-Stretensky formulation, for applications to catamaran and trimaran. In the case of a mathematical hull form for the twin hull and for an equivalent monohull of double beam dimension, the total resistance of the catamaran was found (Eggers, 1955) to be usually greater than that of the monohull ship, but for the length Froude number $F = 0.316$ it becomes slightly smaller than the monohull case when the hull spacing-to-length ratio lies in a narrow range centered about 0.4. This result in fact indicates a condition of a favorable wave-interference effect. The same effect has been further investigated by Tasaki et al. (1963) for a catamaran model. Independent experiments were later conducted by Turner and Taplin (1968) for a 700 ft. cargo catamaran (with slightly asymmetric demihulls) and a 230 ft. submarine rescue ship (ASR). Their test results also show that the residuary resistance of a catamaran can in some cases be less than the sum of the individual demihull residuary resistance. Such favorable wave interference was found to occur under a narrow combination of operating conditions, specifically when the length Froude number is about 0.32 (or $V/\sqrt{L} = 1.05$) and when the spacing/length ratio is around 0.5, which are well in the same regime as reported by Eggers. In addition to the wave-interference effect, Boericke (1959) further proposed a wave suppression mechanism for reducing the surface wave motion by a horizontal hull surface.

3. The New Generation of Catamarans

The recent development, which mostly occurred in the last decade, of catamarans exhibits the tendency to place the major portion of a specified displacement volume at a sufficient depth of submergence and to employ struts of small waterplane area for connecting the submerged hulls and the above-water platform. Such a basic configuration is intended to optimize the viscous resistance per unit displacement volume on one hand, to minimize the wave resistance on the other, and to achieve the favorable motion-stability characteristics at the same time.

The first design of this type was proposed in 1946 by Creed (U.S. Patent No. 2,405,115), which consists of a pair of torpedo like hulls, each connected by one streamlined strut to an above-water cross structure. As a further improvement of the Creed design, Leopold (1968) proposed the Trisec, which is directed toward larger ships in the speed range of 20-80 knots. Based on certain modification of the demihull form (to assume a more flat horizontal stern) and the struts (with a narrow neck form), Meier (1968) and Christensen (1970) described the design of a submarine rescue catamaran (ASR). Further discussions of these designs can be found in the papers by Bond (1970) and Stevens (1972).

For this new class of catamarans, the total resistance naturally should be determined for the system of underwater hulls and the connecting struts. Along this line of approach, Sharma (1968) found that the total wave-resistance of a hull-strut system can be less than the wave resistance of the underwater hull alone when the Froude number is around $Fr = 0.3$.

A special series of designs has been developed at NSRDC to meet certain specifications on the performance, maneuverability, and seakeeping. It has led to the conception of the SWATH (small-waterplane twin hull) CVA (attack aircraft carrier) and ASR catamarans. A new aspect of these designs is the introduction of camber and thickness distribution of the struts as additional parameters for (analytically) optimizing the wave-interference effects and low wave-resistance. The motion and resistance of a SWATH has been discussed earlier by Pien and Lee (1972). A combined theoretical and experimental study has been carried out by Lin and Day (1974) for two specific models, MODCAT III and MODCAT IV. MODCAT III has struts with a coke-bottle shaped water plane but no camber, whereas MODCAT IV has a small camber but no neck formation. The theoretical calculation of their wave resistance is based on the thin-ship theory. Between the experimental residuary resistance and the theoretical wave resistance the agreement is generally very good in both cases, their difference being nearly a constant in the speed range tested, which Lin attributes to the form drag of the system. The result also shows that change in the strut shape has a marked effect on the resistance only at low speeds ($V/\sqrt{L} < 1.5$). It was further found that the MODCAT III has less resistance than that of two individual demihulls within a rather narrow operating range ($1.3 < V/\sqrt{L} < 1.5$, and with the spacing/length ratio $= 0.32$), an interesting finding which also supports the earlier report of Eggers (1955) and Turner and Taplin (1968). The coke-bottle-like shape function of MODCAT III struts was determined by an optimization procedure. In this connection, Maruo's contribution (1964, 1966, 1969) to the subject of semi-submerged ships of minimum wave resistance may have useful applications. Further, Lin and Day (1974) found that the data obtained by towing the model captive are substantially different from those obtained by towing the model free to trim and heave. The problem of sinkage and trim of SWATH demihulls has been investigated by Chapman (1974) based on the thin-ship and slender-body type theory; rough agreement between the theory and experiment was found for simple demihull forms.

In still another variation, the S^3 (semi-submerged ship) developed at NUC by Lang and coworkers (1969, 1970) is most applicable to small and medium sized ships (100 to 15,000 tons) at high cruising speeds (with the Froude number from 1.0 to 2.2), and for missions requiring a high degree of seaworthiness and stability even in rough seas (up to sea state 6 for a 3,000-ton ship). In this high speed range, wave drag is small to negligible while the spray drag becomes significant. Consequently the design criteria are appreciably different from other types of semi-submerged catamarans since the hull form of minimum wave resistance and the wave-interference effects are no longer of importance. The extensive investigation by Lang covers all the relevant aspects of the engineering system design. The drag coefficient C_d (based on the reference area $\nabla^{\frac{2}{3}}$) is about 0.04 to 0.05 for S^3 of several thousand tons, which is quite high compared with equivalent conventional ships. The Froude propulsive efficiency can be as high as 0.8 for a well-designed S^3 at low to moderate speeds, which is higher than that of conventional ships (for $Fr > 1$) and also higher than those of hydrofoil boats and planing crafts when $Fr < 2$. Another salient feature of the S^3 is a system of horizontal fins and control surfaces, attached to the hulls, that can provide dynamic stability and permit full automatic control over pitch, heave, and roll.

A newer version of the SWATH-type craft, called the 190-ton SSP (Stable Semisubmerged Platform), has been designed with the S^3 concept and constructed, and its hydrodynamic performance has been investigated by Lang and Higdon (1974). The test results indicate significant reduction in motion in waves and a significant increase in rough-water speed.

4. Motion in a Seaway

The favorable roll stability and good seaworthiness characteristics in rough seas are two main factors that make the catamarans of the new generation extremely attractive.

For a quantitative assessment of the performance of a ship, of almost any type, in rough water, the concept of subcritical, critical and supercritical regimes of operation (according as the natural period of pitch and heave is shorter, about equal, or longer than the period of encounter with the longest major waves) is useful. This concept, first introduced to the seaworthiness problem by Lewis (1955) and subsequently elaborated by Mandel (1960), has been applied by Lewis and coworkers (1960, 1963) to discuss the motion of unconventional ships, including the semi-submerged vehicles, in a seaway. It is concluded that for high-speed crafts, it is better to aim at supercritical operation in head seas but not in following seas, and the critical regime (in which excessive motions occur, forcing a great reduction in speed) should be avoided as far as possible.

For the highbred catamarans, the period of pitch and heave can be made long by adopting slender submerged hulls and struts of small water-plane area, together with the use of large peak ballast tanks. Once entering the supercritical operation the craft motion will actually decrease as speed is increased.

For further studies of the resistance and motion of catamarans in waves and in rough water see Turner and Taplin (1968), Wahab et al. (1971), Ohkusu and Takaki (1971), Nordenstrom et al. (1971), Jones (1972), Jones and Gerzina (1973), Lee et al. (1973).

5. Structural Analysis and Design

The structural design criteria for catamarans (of the new generation in particular) must take into consideration of the following factors: (1) the required large deck area favoring a large spacing between demihulls, (2) the primary stress consideration is consequently in the transverse direction, (3) weight is critical for high performance catamarans (the structural density of usual catamaran is already 2 lbs/ft^3 higher than a monohull), (4) a safe margin for mean wave impact loads, (5) stress concentrations and material fatigue at thin members and junctions of the craft, (6) dynamic loads in extreme maneuvering, etc. This is one of the most difficult problems, for which the experience and knowledge is very much incomplete. For some discussions of these problems see Lankford (1967), Dinsenbacher (1970), Mansour and Fenton (1973), Aronne et al. (1974).

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